SRNL-RP-2010-01666, Revision 0

Key Words:
in situ decommissioning
sensor
remote monitoring
end state

Retention: Permanent

DEVELOPMENT OF A REMOTE MONITORING SENSOR NETWORK FOR *IN SITU* DECOMMISSIONED STRUCTURES

Panel Report

November 2010

Savannah River National Laboratory
Savannah River Nuclear Solutions
Aiken, SC 29808

Prepared for the U.S. Department of Energy Under Contract Number DE-AC09-08SR22470

SRNL
SAVANNAH RIVER NATIONAL LABORATORY

This page intentionally left blank.

On October 19-22, 2010, an independent expert panel of scientists and engineers met to assist the Department of Energy (DOE) and the Savannah River National Laboratory in developing a technical report that recommends the best sensing and concrete technologies for monitoring and isolating contaminants within highly-radioactive nuclear structures that are placed in the DOE *in situ* decommissioning program. This document identifies the recommendations of the panel for short- and long-term objectives needed to develop a remote monitoring network for the C Reactor Building at the Savannah River Site.

The members of the panel are:

Nicholas J. Carino, Ph.D.
In 2004, Dr. Carino retired from the National Institute of Standards and Technology (NIST), after 25 years of service as a research structural engineer. From 1974 to 1979, he was an assistant professor at The University of Texas at Austin, where he taught courses in mechanics, construction materials, and reinforced concrete design. His principal research activities at NIST were in the areas of in-place testing of concrete for strength, nondestructive methods for flaw detection in concrete, and high-performance concrete. He was also involved in several NIST investigations of structural performance including the World Trade Center disaster of 9/11. Dr. Carino is a Fellow of both the American Concrete Institute (ACI) and ASTM International. He served as Chair of the ACI and ASTM committees on nondestructive testing of concrete. He has received numerous awards from ACI and ASTM for his research and contributions to standards development. Most notably, he received the ACI Wason Medal for Materials Research four times for work done with colleagues at NIST. He served as Chair of ASTM Committee C 09 on Concrete and Concrete Aggregates. He is the recipient of the 2002 ASTM Award of Merit and the 2009 Katharine and Bryant Mather award for his leadership, service, and outstanding contributions to the work of Committee C09. He is co-editor of the internationally recognized Handbook on Nondestructive Testing of Concrete. Dr. Carino received undergraduate and graduate degrees from Cornell University in Ithaca, New York.

Victor Li, FASCE, FASME, FWIF, FACI
Dr. Victor Li is the E. B. Wylie Collegiate Professor of Civil and Environmental Engineering at the University of Michigan, Ann Arbor. He led the research team that invented Engineering Cementitious Composites, popularly known as “Bendable Concrete”. Professor Li received the Distinguished Faculty Award from the University of Michigan in 2006. In 2005, he received the Stephen S. Attwood award bestowed by the College of Engineering at the University of Michigan. In 2004, Professor Li was honored by the Technical University of Denmark with a “Doctor technics honoris casusa” in recognition of his “*outstanding, innovative contributions to materials research and engineering and providing our society and the construction industry with new, safe and sustainable building materials*”. Professor Li is a Fellow of the American Society of Civil Engineers, the American Society of Mechanical Engineers, the World Innovation Forum, and the American Concrete Institute.

Gail L Heath
Mr. G. Heath is a Senior Scientist at the Idaho National Laboratory. Mr. Heath received his M.S. in Geophysical Engineering from the Department of Mining and Geological Engineering at the University of Arizona and his B.S. in Geology at Southern Utah University. Mr. Heath is currently the national chair for the Dam and Levee Safety Technical Working Group subcommittee of the National Hydrological Warning Council. The pursued research areas are in fluid and contaminate

transport in fractured media, thermoremediation, and acid-mine drainage monitoring using long-term, integrated, and self calibrating remote controlled monitoring and data management systems.

Gangbing Song, Ph.D.
Dr. G. Song is the founding Director of the Smart Materials and Structures Laboratory and a Professor of both Mechanical Engineering and Electrical & Computer Engineering at the University of Houston. Dr. Song is a recipient of the National Science Foundation (NSF) CAREER grant in 2001. Dr. Song received his Ph.D. and M.S. degrees from the Department of Mechanical Engineering at Columbia University in the City of New York in 1995 and 1991, respectively. Dr. Song received his B.S. degree in 1989 from Zhejing University, P. R.China. He has expertise in smart materials and structures, structural vibration control, and structural health monitoring and damage detection. He has developed two new courses in smart materials and published more than 200 papers, including 80 peer reviewed journal articles. Dr. Song is also an inventor or co-inventor of 3 US patents and 6 pending patents. He has received research funding in smart materials and related research from NSF, the National Aeronautics and Space Administration (NASA), Department of Education, Texas Higher Education Board, Texas Space Grant Consortium, University of Texas Medical Branch, Ohio Space Grant Consortium, Ohio Aerospace Institute, Ohio Department of Transportation, HP, OptiSolar, and Cameron.

Chuji Wang, Ph.D.
Dr. Chuji Wang is an Associate Professor in the Department of Physics and Astronomy at Mississippi State University. He received his Ph.D. degree in Chemical Physics at the University of Science and Technology of China in 1998. His research interests include diagnostics of low temperature atmospheric plasmas and the development of novel fiber optic sensors and sensor networks, such as time-domain fiber loop ringdown sensors and noninvasive breath gas sensors, using cavity ringdown spectroscopy techniques. He has authored more than 50 peer-reviewed journal publications and holds four US patents in the fields of fiber loop ringdown sensors and ringdown instrumentation. His current research is supported by one DOE and two NSF grants, including the one from the NSF CMMI-Sensors and Sensing Systems program.

Paul Ziehl, Ph.D., P.E.
Dr. Paul Ziehl is an Associate Professor of Civil and Environmental Engineering at the University of South Carolina and is the director of the Structures Research Laboratory. He is the recipient of the American Society for Engineering Education Southeastern Section New Faculty Research Award, 2007, and is currently directing U. South Carolina's effort in the 5 year $14 million NIST project "Self Powered Wireless Sensor Network for Structural Bridge Health Prognosis". Dr. Ziehl received his Ph.D. and M.S. degrees from the Department of Civil Engineering at the University of Texas at Austin in 2000 and 1997, respectively. Dr. Ziehl received his B.S. degree in 1989 from California Polytechnic State University, San Luis Obispo. He has expertise in structural health monitoring, nondestructive evaluation, design and analysis of reinforced concrete structures, strengthening/retrofit of buildings and bridges, and composite materials. He is an active writing and voting member of several international American Society of Mechanical Engineers (ASME) and ACI technical committees. He has developed a new course in reinforced concrete/composite materials including nondestructive evaluation and has authored more than 100 related technical publications and presentations. He is the lead author of "Inspection, Testing, and Monitoring of Buildings and Bridges" to be published by the NCSEA. He has more than thirty related sponsored research projects and has received funding from NIST, NSF, NASA, MDA, US Air Force, US Army, USDOT, FHWA, SCDOT, TXDOT, ALDOT, and NYSDOT.

Support to the panel has been provided by the Savannah River National Laboratory:

Richard J. Abitz, Ph.D.
Sheryl R. Bush
Blythe A. Ferguson, Ph.D.
Kristine E. Zeigler, Ph.D.

DISCLAIMER

Printed in the United States of America

Prepared for
U.S. Department of Energy

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

ACI	American Concrete Institute
ACP	Area Closure Projects
AE	Acoustic Emissions
ASCE	American Society of Civil Engineers
CFRP	Carbon-Fiber Reinforced Polymer
COTS	Commercial Off The Shelf
D&D	Deactivation and Decommissioning
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
ERT	Electrical Resistivity Tomography
FBG	Fiber Bragg grating
FOS	Fiber Optic Sensor
ftp	File Transfer Protocol
FY	Fiscal Year
ISD	*In Situ* Decommissioning
PES	Piezoelectric Sensor/Sensing
PI	Principal Investigator
PZT	Lead Zirconate Titanite
R&D	Research and Development
SQL	Structured Query Language
SRNL	Savannah River National Laboratory
SRS	Savannah River Site

1.0 EXECUTIVE SUMMARY

This report presents the recommendations of an independent expert panel of scientists and engineers as to the short- and long-term objectives needed to develop and deploy a remote monitoring network in the C Reactor Building (105-C) at the Savannah River Site by fiscal year 2016 (FY16). The approach outlined in this report has an estimated cost of approximately $28M (FY11-FY16). The recommendations include construction and operation of sensor test beds and a monitoring program that includes a variety of sensor systems to monitor physical and chemical conditions of 1) the above grade portion of 105-C, 2) the grouted, sub grade portion of 105-C, and 3) the subsurface conditions below 105-C. Although the recommendations in this report chart a specific path that leads to a remote monitoring system for 105-C, the panel is in agreement that the recommended remote monitoring path is appropriate for any structure slated for *in situ* decommissioning.

This page intentionally left blank.

2.0 INTRODUCTION

The Department of Energy (DOE) is presently implementing permanent entombment of highly contaminated, robust nuclear structures via the designated end state of *in situ* decommissioning (ISD) [36]. Entombment of an ISD structure is the placement of cementitious grout materials below grade up to ground level. This will immobilize any residual contamination contained within the building and structurally stabilize the building [7]. In the case of a reactor building undergoing ISD, the above grade structure over the Disassembly Basin areas will be demolished and removed, and a concrete cap will cover the grouted area [20]. The reactor vessel itself will be filled with grout to the maximum practical extent and capped with a reinforced concrete cap [7].

The design and deployment of a remote monitoring program throughout the DOE complex for ISD structures and their entombed contaminants is one of five thrust areas identified by the DOE as a key technology and/or knowledge gap to be addressed [26]. Designing a remote monitoring program requires an understanding of the changes in and around the ISD closure facility over time, with the deployment of appropriate sensors to detect those changes [21]. Along with a remote monitoring system, a correlation of sensor and subsurface changes will be established to define limits with respect to monitoring and remedial actions. The monitored data must be of sufficient type and quality to allow the DOE to assure its stakeholders that the ISD structure is performing in accordance with the thousand-year lifetime prediction of the concrete-degradation model and that entombed contaminants are not being released to the environment [8].

Monitoring parameters are tied to three key data needs: assessing the structural integrity of the facility, assuring concrete cap stability, and demonstrating immobilization of contaminants. Sensors that monitor for strain, crack growth, and corrosion will provide data for performance models that evaluate long-term stability. The mobilization of radionuclides with long half-lives within the facility tends to drive risk assessments, and monitoring for fluid mobility within the facility and grout monolith will provide opportunity for cost-effective intervention before the release and detection of contaminants at monitoring wells.

This report presents short- and long-term objectives, with associated costs, to develop and deploy a remote monitoring network in the C Reactor Building (105-C) at the Savannah River Site by fiscal year 2016 (FY16). The approach outlined in this report has an estimated cost of approximately $28M (FY11-FY16). Although this report charts a specific path that leads to a remote monitoring system for 105-C, the panel is in agreement that the recommendations are appropriate for ISD structures throughout the DOE complex.

The short-term objectives (FY11) are to demonstrate the capability of sensor networks to monitor fluid flow and transport through grout and concrete by installing embedded sensors in an offsite meso-scale test bed. Also, higher performance formulations for concrete caps to be placed over the reactor and disassembly basin will be compared against the current formulation. To accomplish this, collaborations will be established between Savannah River National Laboratory (SRNL), Area Closure Projects (ACP), and non-Savannah River Site (SRS) Principal Investigators (PIs).

Long-term objectives (FY12-FY16) are focused on deployment of remote monitoring systems in a full-scale test bed prior to installation into Building 105-C and the subsurface of 105-C. Collaboration between SRNL, ACP and non-SRS PIs are to continue with the joint production of work and design documents. Another important aspect of the long-term objectives is the identification and funding of two to three viable research programs that can develop the next generation of physical and chemical sensors.

The panel recommends a specific path that leads from short-term objectives to long-term deployment of a remote monitoring system for 105-C. Although this path includes test beds and sensor development, the panel is in agreement that any recommended path for monitoring an ISD structure needs to 1) recognize the logistical complexity associated with wiring and continually merging data from multiple sensor systems, 2) understand the data collected from a remote monitoring system before interpretation, and 3) form a robust team of collaborators with clearly designated responsibilities. By addressing these issues, a successful deployment of a remote monitoring system will be realized.

3.0 ONGOING EFFORTS

Throughout the life of the project, restructuring of collaborations, associated documentation, and data communication are essential. After completion of the initial 105-C project, data communications will continue to be updated as new technology becomes available. Collaborations will be established and expanded as new research and development areas are identified.

Participating research organizations, subcontractors, and other collaborators are to be identified and subcontracts set up prior to developing test plans, specifications and procedures. It is vital that specific work plans be developed throughout the life of this project. For actual deployment, briefings and meetings are to occur between the appropriate parties. Videos to demonstrate the correct installation methods along with question and answer sessions will be used to train personnel who will install and wire the sensor systems.

It is necessary that specifications for system materials and construction plans be defined and documented. The construction plan will need to include: details of sensor placements, wiring from sensors to data loggers, data communication needs, power requirements, and power sources. While conducting this communication and construction documentation for both test beds, all opportunities for training of contractors to implement the material and sensor technologies in Reactor Building 105-C will be sought.

Along with the work documentation, there will be the associated need for establishing data communication protocols. Data communication and transmission from sensor to logger and logger to computer or server will be vital to the success of the monitoring program. Several integration issues for recording, storing and accessing data need to be addressed. This is especially important because limits of transmission may exist at the ISD site. Communication plans are beginning to be addressed but the communication requirements will continue to be vital for the duration of this project.

Figure 3.1 outlines the basic requirements to obtain, transfer, store, manipulate, and distribute data from the remote sensor systems. Among the major components needed are a site network infrastructure that is sufficient to handle a very large volume of data, and a 24/7 facility for hosting the monitored data servers that provides redundant power and cooling with emergency UPS (battery) power, daily data backup (with up to 30 day retention), and ample network connectivity.

A user-interface or "dashboard" allowing selected users to display current and historic data is also needed. This interface will allow the user to interact with the data with relative ease. Structured Query Language (SQL) reports are required to interface with other monitoring and modeling systems to be developed. Additionally, the panel strongly recommends that an ftp server be available for off-site access. This off-site access will offer collaborators a link to data files for evaluating the performance of the monitoring systems.

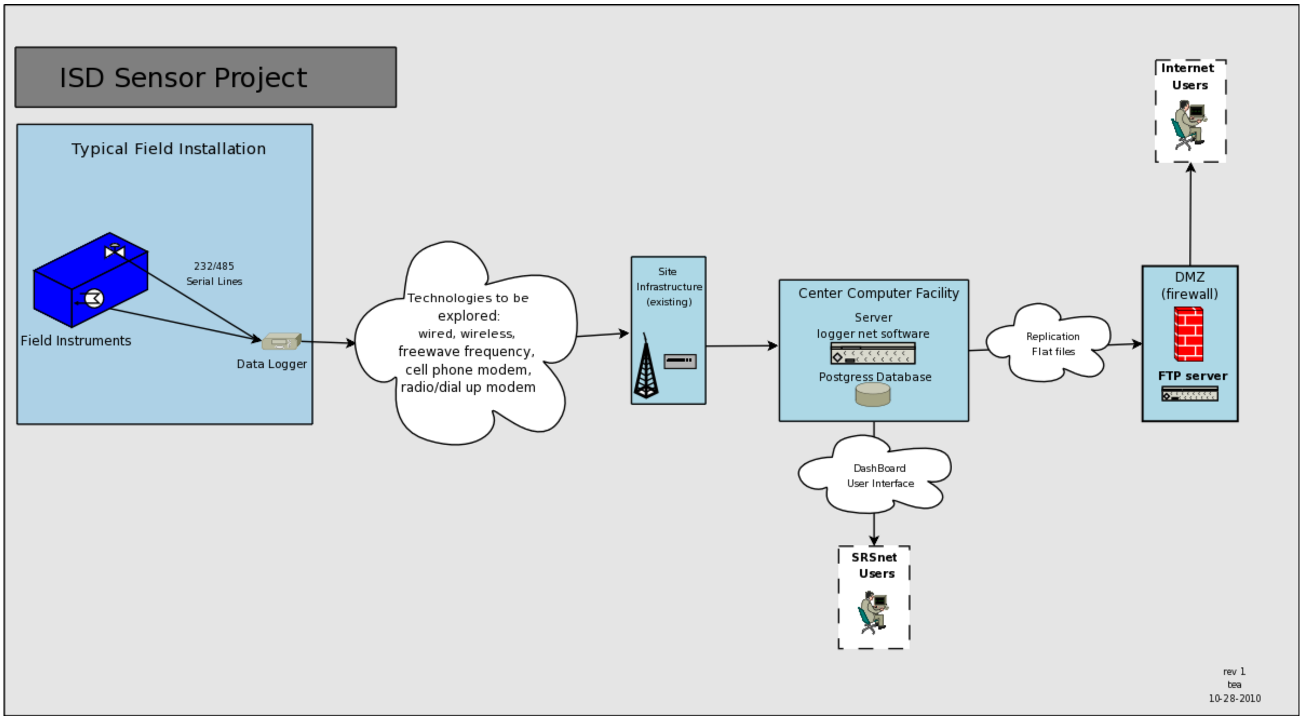

Figure 3.1 Requirements to obtain, transfer, store, manipulate, and distribute data from the remote sensors systems

At the data collection point, the use of one or more serial data loggers with onboard memory and internet connectivity will provide the ability to make the data available to servers located at great distances, much farther than practical by direct serial connection. This arrangement will allow the system to withstand temporary outages in the network and/or servers without data loss. Should the network connection and/or database server become inoperative, data will be downloaded when the network is restored (up to the capacity of the data logger). While the actual data logging and associated hardware must be obtained, installed and configured, the commercially available models are essentially identical to systems already operating.

One major component depicted in Figure 3.1 does not currently exist and will require further evaluation. At present, the distance between an appropriate location for the data logger(s) and the site network is approximately 1,500 meters. Several potential mechanisms exist for bridging this distance including: extending a "hard-wired" connection to the site intranet, evaluation of wireless Ethernet radio technologies, and a cell phone modem. Based on the outcome of that evaluation, which is currently underway, the preferred method(s) of connection will be implemented in the short term objectives. Future communication technologies will be evaluated as identified.

4.0 SHORT-TERM OBJECTIVES

The panel identifies the following objectives for the remote monitoring program for a funding level of $1.2M in FY11:

- Testing the performance of commercial off-the-shelf (COTS) and laboratory-tested sensors embedded within the grout of an off-site meso-scale test bed;
- Performing laboratory tests to determine the best concrete formulation and instrumentation for the disassembly basin and reactor concrete caps; and
- Identifying R&D sensor technologies to support long-term deployment in the full-scale test bed.

During this fiscal year, collaborations with universities, other national laboratories, and private sector companies will be established to ensure that the meso-scale test bed is outfitted with pertinent sensors. Efforts will also continue on establishing the best data communications and testing protocols at the meso-scale test bed. Documentation during this time will ensure the testing is planned and implemented in a controlled manner to produce valid results within the estimated costs and on schedule. Detailed descriptions of sensor specifications, testing plans, procedures, and limitations will be documented prior to sensor installation and testing.

4.1 MESO-SCALE TEST BED

The meso-scale test bed study is required to determine optimal methods for sensor infrastructure and installation in an entombed ISD structure, as well as data collection to understand fluid flow and possible transport mechanisms within the grout monolith. A meso-scale test bed will be designed and constructed at an offsite location to evaluate a suite of sensors and gain an integrated understanding of the complete system operations. The primary goal of the offsite meso-scale test bed is to identify limitations with the sensing systems and incorporate the findings into recommendations for technologies that will meet the expectations for monitoring various parameters of ISD structures. Secondary goals include: demonstration of sensor configuration and wire arrangement for different sensor systems, confirmation of sensor placement and stability during grout field pours, and understanding instrument variation and performance in a large grout monolith. An offsite 10-foot diameter by 8-foot high meso-scale test bed is proposed due to insufficient funding in FY11 for development of a full-scale test bed at the 105-C site.

Data from the meso-scale test bed will be evaluated to assess the accuracy and sensitivity of the various sensor systems and to determine if different sensor types produce measurements that can be correlated to boost decision confidence. Difficulties in deploying different sensor types and interpreting data will be documented to provide a written record of lessons learned for inclusion in operational protocols. Information and data obtained from this work will serve as the baseline data set for the selection of future instruments, including the design and deployment of sensor networks in the full-scale test bed at 105-C (FY12).

4.1.1 Sensor Types

Characteristics that must be addressed related to the various types of sensors include the following:

- Embedding of sensor modules within grout: location of the point of deployment, physical tolerances (mechanical bending, crushing, impact, etc.), and physical dimensions of sensor modules;

- Installation: connection and multiplexing of various sensor types (electrical vs. fiber) within the sensor system, wiring from the sensor to the logger and transferring data from the logger to a user;
- Power requirements: estimated total power for all of the sensor types; tolerance of power fluctuations, consequences of power outage (must be self protected or insensitive to power outage, short recovery times);
- Power sources: flexibility of using land lines, batteries, and solar cells (with DC-AC converters);
- Data acquisition system requirements: instrumentation integration, compatibility, environmental conditions, sensor drift, longevity; and
- Data outputs from sensors: Data management and transmission, distribution, formatting, processing, quality assurance/quality control (QA/QC), and reporting protocols.

Based on the panel discussions, fiber optic sensors (FOS), electrical resistivity tomography (ERT), advanced tensiometers (AT), and active/passive piezoelectric sensors (PES) are some of the systems recommended for the test bed as discussed below.

4.1.1.1 Fiber optic sensors

The specific advantages of optical fiber sensors (FOS) for long-term *in-situ* monitoring of decommissioned buildings include longevity and inherent network ability to form sensor networks. The fiber optic sensor heads and signal transmission waveguides are made of silica and can therefore resist degradation. Fiber optic sensors which were embedded in a bridge twenty years ago for continuous, long-term monitoring are still operational [28]. The inherent network ability enables measurement of various parameters, such as displacement, strain, moisture, temperature, acceleration, and corrosion, along a single fiber, significantly reducing wiring and installation cost.

Since the invention of the fiber Bragg grating (FBG) in the 1970s, FBG-based fiber optic sensors have been widely accepted by researchers and engineers for structural health monitoring because of their distinguished advantages, such as small size, distributed sensing ability, high sensitivity, high precision, durability, longevity, and electromagnetic interference immunity. FBG-based fiber optic sensors have been successfully utilized to perform structural health monitoring for various civil infrastructures, such as buildings [38], piles [6], concrete bridges [34], and underground structures [22].

FBG based displacement sensors, including long gauge strain sensors and temperature sensors for concrete structures, have recently been developed. The long gauge strain sensors, when deployed in a distributed fashion, can be used to monitor new crack development. Conventional strain sensors with very short gauge length (less than 1 inch) are not suitable for detecting crack onset and growth. FBG long gauge length strain sensors, which can cover 9 inches and possibly more with further development, are well suited for the task of detecting crack onset and growth.

Concrete structures of decommissioned nuclear facilities may have existing cracks and will be subjected to new crack development. Monitoring of the existing cracks is of great importance. Special attention should also be paid to the movement of expansion joints. FBG displacement sensors are well suited for these tasks.

In addition to the FBG-based sensing mechanism, wavelength-dependent absorption and scattering sensing mechanisms are also widely implemented in FOS for chemical sensing to achieve identification and quantification of chemical species.

4.1.1.2 Electrical resistivity tomography (ERT)

Electrical resistivity tomography (ERT) is a three dimensional application of resistivity surveying with time lapse capabilities. Resistivity has several unique characteristics that make it appealing for process monitoring and characterization field studies [18]. The following is a list of those advantages:

1. Electric conductivity is sensitive to important hydrological properties, including water content, solute concentration and temperature.
2. ERT surveying is a volumetric method that can be automated, and each measurement is inexpensive and relatively rapid, compared with most direct and indirect measurement methods.
3. Used in a time differencing mode, parameter resolution and sensitivity from ERT is greatly enhanced over the single shot characterization approach.
4. Unlike direct point measurement methods, the sample volume of ERT ranges from tens of cubic centimeters to tens of cubic meters. Through survey design the user can exert some control on both the size and the spatial sensitivity distribution within the sample volume.
5. ERT is scale independent so results from lab scale, meso-scale and field-scale experiments match across the different sensing volumes. [19]
6. Recent technological advancements [15] have reduced measurement times, increased measurement sensitivities, improved analyses of results, increased mobility of equipment, and significantly reduced acquisition costs.

As a result of these characteristics, ERT is an excellent technology for characterizing and monitoring hydrologic investigations, contaminant flow, remediation, injection studies such as steam, polymers, water, CO_2, as well as hydrologic parameter estimation. ERT is the only method available that is capable of three dimensional volumetric mapping of subsurface fluid plumes and system dynamics over time.

In the past several years, improvements have been made to ERT data collection hardware and controlling software including the exponential growth in the number of uniquely addressable electrodes as well as an increase in the number of channels and simultaneous measurements. In addition newer systems have been produced with hardware and software specifically designed for autonomous monitoring capabilities that allow low maintenance continuous measurements for highly detailed time-lapse applications. The faster data collection and increase in the number of useable sensors enables the emplacement of larger and denser networks for greater resolution while decreasing the uncertainty and non-uniqueness related to low spatial data density.

4.1.1.3 Advanced tensiometers

Advanced tensiometers (AT) are pressure transducers that provide direct point measurement that will respond to wetting and drying events in the vadose zone. Advanced tensiometers were developed to meet the need for an improved understanding of unsaturated flow and transport in deep vadose zones

[16]. They have been demonstrated to be reliable, require little maintenance, and are effective tool for mapping soil water potential over areas the size of landfills and disposal sites. They measure soil water potential (pressure) which determines the direction and rate of water movement in the unsaturated zone. Information regarding the distribution of water potential and liquid water flux is critical for predicting soil drainage and the transport of dissolved contaminants to underlying aquifers. Advanced tensiometers have provided sensitive and direct soil water potential measurements to estimate flux and directions of flow at large sites for over a decade [17].

Data from the ATs are essential to providing the rate of water and contaminant movement because gradients in water potential determine the direction of water flow. The ATs are effective detectors for monitoring wetting-front movement or steady flow conditions. When wetting fronts are observed in the subsurface, it is ample evidence that water is rapidly moving through the sediments. Monitoring wetting-front movement requires installing ATs at different depths so that the time of arrival at each depth can be used to calculate the wetting-front velocity. Correlating the wetting-front data to weather and site management practices, provides the behavior of water movement within the deep vadose zone. The advanced tensiometer's soil water potential data directly supports vadose zone modeling activities, allowing direct comparisons between field soil water potentials and model predictions. Subsurface barometric pressure transducers and thermocouples are installed to obtain data from various levels below ground surface.

4.1.1.4 Piezoelectric sensors

There are two broad approaches to piezoelectric sensing (PES) for detection of cracks and crack growth: active and passive. High fidelity COTS sensors and data acquisition systems are available and should be incorporated in the test beds due to their high level of sensitivity and demonstrated robustness in similar field applications (buildings and bridges) [9, 10, 12].

The primary advantage with active piezoelectric sensing is that the material can be interrogated at anytime. The accompanying disadvantage is that energy is required to conduct the interrogation and active sensing may be insensitive to cracks that are parallel to the direction of wave propagation. However, with active piezoelectric sensing, if a significant array of sensors is used the potential exists for imaging of crack surfaces. In recent decades, piezoelectric-based active sensing approach has been researched and implemented in the health monitoring of concrete structures. Zhang *et al*. [44] experimentally studied PZT (Lead Zirconate Titanite, a type of piezoceramic material) active health monitoring for fatigue accumulative damage of concrete beam containing nano-particles (TiO_2) for pavement. Zhao and Li [45] embedded PZT sensors into concrete pillar to identify the vibration parameters of structure.

The primary advantage of passive piezoelectric sensing (also referred to as acoustic emission (AE) monitoring) is that the formation of a crack within the material generates a stress wave that causes the sensor to become excited. Therefore active cracking events can be detected and located [14, 31, 27, 42]. Another advantage is that the energy requirements are low in the absence of distress because the sensor is simply not activated until distress occurs. Locations of cracking events or other sources such as leakage can be found through a number of approaches including triangulation based on time-of-flight and moment-tensor analysis [43]. The extreme sensitivity of acoustic emission testing makes it a promising sensing approach because cracks do not need to be visible and the sensors only need to be located in the general vicinity of active cracking (within a 10 foot radius) to detect and record the event [40]. Because the speed of the stress wave can be estimated or measured on test specimens of the material, it is possible to locate the origin of cracking within thick materials, such as concrete slabs or the grout monolith. To be compatible with concrete material, a new cement-based piezoelectric composite sensor was developed to detect AE signals generated by formation of micro-cracks [23].

For the meso-scale test bed, it is recommended that both active and passive piezoelectric sensing be deployed. Active piezoelectric sensing will take advantage of the conduits and sensor arrays implemented for the ERT method. Because the active piezoelectric sensors generate mechanical stress waves within the material the information will be complementary to the ERT approach. Active piezoelectric sensing has the potential to detect cracks that form between sensor arrays due to reflections from crack surfaces, and thus lead to the detection and location of water migration through cracks in the grout. In addition, the presence of moisture will increase the wave speed, and this may provide confirmation of results inferred from ERT.

4.2 HIGH-PERFORMANCE CONCRETE FORMULATIONS

The panel believes that superior concrete formulations exist compared with that being used to cover the disassembly basin and reactor. High-performance concrete formulations exist that have enhanced mechanical and durability properties and should be able to maintain cap integrity for hundreds of years. This objective has two tasks:

1. Evaluate sensor performance and develop data interpretation strategies in a reduced-scale concrete cap constructed with the present portland cement/KIM301 mixture.
2. Demonstrate through specialized laboratory tests an alternative mixture with higher performance compared with the current portland cement/KIM301 mixture being used at ISD structures.

4.2.1 Sensor Evaluation in a Model Cap

In order to evaluate plausible sensors and their performance in a reinforced cap concrete, and prior to conducting studies with a full-scale test bed at the SRS site, it is recommended that a concrete slab cast on grade (or cap) be used. The cap is needed to assess the viability of different sensing approaches for the degradation mechanisms that can be expected over the short- and long-term including micro-cracking, shrinkage cracking, and corrosion of reinforcement. The material for the slab is the 3000 psi concrete with an additive intended to provide for crack "healing" that is used in the cap for the P and R reactors. The slab size is 20 foot long by 20 foot wide by 7 inches thick. Measurement parameters are to include detection of crack growth and location, corrosion monitoring, and moisture content. To accelerate reinforcement corrosion, the slab will be subjected to outdoor exposure and portions will be subjected to accelerated corrosion by impressed current. Sensor types to be evaluated include fiber optic (strain, moisture, and temperature), resistivity sensors, vibrating wire strain gauge, thermocouples, COTS passive/active PES both embedded and arranged in surface grids, and nano-based piezo-resistive films. Another technology to be explored for the caps is “smart aggregate”.

Smart aggregates are low-cost, piezo-ceramic-based multi-functional devices that are capable of performing comprehensive monitoring of concrete structures, including monitoring early-age strength development, impact detection and evaluation, and structural health monitoring. For impact detection, experimental results show that the peak value of the signal from the embedded piezoceramic is proportional to the impact force. In addition, embedded smart aggregates can measure the stress level during extreme events such as earthquakes. For structural health monitoring, a smart aggregate-based active sensing system has been developed. In the active sensing system, one smart aggregate is used as an actuator to generate a stress wave while the other smart aggregates are used as sensors to detect the response. Based on the analysis of the received waveforms, an index can be formed to evaluate the severity of the damage. Experimental results show that the proposed structural health monitoring method is better than traditional methods with regards to detection of the existence and evaluation of crack severity [32, 33). In previous study, smart aggregates were successfully utilized to perform the health monitoring of various large scale concrete structures, including concrete bridge bent-cap [33], concrete frame [32], shear wall [41], and circular columns [25,13]. Smart aggregates will be embedded into the proposed model cap structure to detect the onset and growth of cracks and to estimate the locations.

The data from the model cap study should include concrete strain, temperature variation, cracking behavior (location, width, and growth), corrosion rate, and moisture distribution as a function of time. The data will be used for evaluating the accuracy and sensitivity of the various sensors. Based on the model cap study, recommendations on sensor type, density, and placement locations and installation procedures shall be made for the full-scale test cap in the long-term objectives.

4.2.2 Cap Concrete Compositions and Performance

The cap concrete provides the primary barrier to environmental moisture for the disassembly area and provides a secondary moisture barrier for the reactor area. The ability of the cap concrete to function as a moisture barrier depends on its inherent resistance to moisture penetration and its ability to remain crack free. In addition, for the reactor cap, impact resistance to falling debris from collapsing structures above and adjacent to the reactor should be considered.

In the event that cracks form, the ability of the cracks to restrict the migration of moisture is a key factor in the performance of the cap as a moisture barrier. The material chosen for the cap concrete in the P and R reactors has been described as a 3000 psi concrete with an additive (KIM 301) that is intended to provide for crack "healing". The objective of the proposed investigation is to compare the performance of this cap concrete with alternative concrete mixtures.

The panel is concerned that a design strength of 3000 psi may not be consistent with a service life on the order of 1000 years. The panel recommends that the concrete have a 28-day specified strength of at least 5000 psi, and at the same time have a low tendency for cracking due to volume changes. To meet durability concerns, the panel recommends the following research to investigate the concrete mixture used for the proposed caps at 105-C.

A literature search shall be conducted to gather performance data of concrete incorporating the "crack healing" additive used in the cap concrete for the P and R reactors. An experimental program shall be designed and three test methods will be used to compare alternative concrete mixtures with the cap concrete that has been selected for the 105-P and 105-R structures.

Test for electrical conductivity: The electrical conductivity of saturated concrete is an indirect indicator of the resistance of concrete to fluid penetration, because the factors that affect resistance to fluid penetration also influence electrical conductivity. Measurement of electrical conductivity is a preferred test method [3] because results are obtained in a short period of time and it is possible to compare concrete mixtures that are too impermeable for testing using traditional hydraulic permeability methods.

Test for resistance to cracking: As concrete undergoes hydration and drying, there are volume decreases that, if restrained, will lead to cracking. Whether a given concrete will crack as a result of early age volume changes is difficult to predict because there are many factors that affect concrete's resistance to cracking. The relative performance of alternative concrete mixtures with respect to resistance to cracking due to volume changes can be evaluated using the restrained-ring test method [4]. Data on cracking performance (number of cracks, crack width and time of occurrence) will be collected and used as a basis for comparing relative resistance to cracking due to early-age volume change and drying shrinkage.

Test for permeability of cracked concrete and healing of cracks: This test aims to address the penetration of water through the cap concrete material after cracking occurs. It is also meant to evaluate the crack healing behavior of concrete. While there are no ASTM test methods for measuring water permeability of concrete, the panel recommends a constant head permeability test (similar to [5]) to be performed on post-cracked specimens from the restrained ring test. The post-cracked specimen will be used to collect data on permeability as a function of time. If healing occurs over time, a reduction of permeability will be detected. Hence the rate of change of permeability can be documented.

Based on the test results from the laboratory evaluation of alternative mixtures, recommendation of the cap concrete material to be used in the full-scale test bed (discussed under long-term objectives) shall be made. Documentation of basic material properties and test data shall be provided. Placement procedures and curing conditions, as well as quality control methodologies shall be made available.

4.3 IDENTIFICATION OF R&D SENSOR TECHNOLOGIES

Currently, sensor technologies are lacking to measure fluid concentrations of common ions and radionuclides associated with entombed materials in facilities. The panel is in agreement that research and development (R&D) of custom sensors and sensor networks is necessary in order to meet the specific detection criteria associated with monitoring ISD structures. A challenging issue in the development of new custom sensor networks is the unprecedented large-scale sensor deployment envisioned for the 105-C structure, in terms of the total number of sensors and the wide range of sensor distribution. Ideally, sensors should be capable of measuring both chemical concentrations inside the grout monolith and physical characteristics of the structure, with features of high measurement sensitivity, calibration free, little to no maintenance, high network caliber, low power consumption, and long life expectancy. New sensors need to exploit novel sensing concepts, advanced nanotechnologies, and smart materials to help address the aforementioned challenges. Research to design and develop these new sensors will require collaboration and technical exchange with university and industry research groups. Promising research programs must be identified in FY11 and research initiated in FY12 to allow two to three years of R&D prior to deployment of the sensors/sensor network in the full-scale test bed and limited installation in 105-C.

This page intentionally left blank.

5.0 LONG-TERM OBJECTIVES

Successful deployment of a remote monitoring system in 105-C is based on total funding of approximately $27M over five years (FY12-FY16) and executing the scope discussed in the following objectives:

- Design and construct a full-scale test bed, including the concrete caps, to understand sensor performance in the mimicked conditions of 105-C;
- Design and install a subsurface monitoring network that can detect fluid migration under the -40 foot elevation floor slab of 105-C;
- Collaborate on the research and development (R&D) of new physical and chemical sensor technology for both the grout and building structure;
- Deploy structural sensors in above-grade rooms and roofs of 105-C;
- Recommend the best high-performance concrete formulation for cap construction and provide performance data to ACP engineering for design and construction; and
- Deploy physical and chemical sensors in below-grade rooms of 105-C and in the concrete caps placed over the reactor and disassembly basin.

Data communications plans and project collaboration through the preparation of contract documents, test plans, and engineering designs and specifications will continue to be implemented during the life of the project. Efforts will also continue to improve and expand upon the communication network between the sensors/loggers/server. As site rules and policies change, alternative means of communication will be pursued. With the expansion of the sensor network and the addition of funded R&D sensor technologies in the larger test bed as well as in the ISD structure, the user-interface will be adjusted to include new sensors and data interpretation algorithms/protocols. Work is ongoing in the area of wireless and self-powered systems and this work will be extended to optimize the sensor network to the unique power and transmission requirements of the evolving project.

5.1 CONSTRUCTION OF A FULL-SCALE TEST BED AT SRS

Using the lessons from the meso-scale testbed and cap model, a full-scale test bed will be constructed to mimic in situ conditions and understand the physical environment that surrounds the embedded sensors, installation logistics, sensor performance under construction conditions, and data transmission and interpretation protocols, prior to deployment of sensors in the structure. It is the best approach for obtaining the needed information to identify and mitigate risks associated with a 'one-chance' sensor deployment in 105-C. The full-scale test bed will serve as a demonstration and development platform at a scale that allows for sufficient realism in terms of geometry and structural systems. The full-scale test bed will provide the opportunity to look closely at the structural elements such as a representative reinforced concrete wall, a grout monolith, and a concrete cap. Installation conditions to be assessed include placement of the sensors, which is to include interfacing between the existing structure, joints and cracks, as well as the loading that will be placed on the sensor nets and vertical instrument strings as the grout is placed in lifts. During this testing, modifications or changes may be needed for the final deployment of sensors in the ISD structure. High-performance concrete formulations tested and recommended from FY11 will be used to construct caps on top of the test bed, and these caps will be instrumented with mechanical and chemical sensor arrays. Data collected from the full-scale testing will lead to a better understanding and optimization of the sensor networks for 105-C deployment.

A candidate location for this test bed is an empty water basin constructed next to 105-C. A portion of the water basin's concrete wall and floor basin can be partitioned off for the full-scale test bed. The 20 foot depth of the basin is ideal for testing because it is similar to the distance between the -20 foot ceiling and -40 foot floor slab in 105-C. It is envisioned that many of the sensors placed below grade and embedded in grout will be hung from cable strings that extend from the ceiling, so a 20 ft deep full-scale test bed will simulate grout load and forces on the sensors during placement and also mimic the lift geometry.

Sensors deployed in the full-scale test bed will be chosen based on the results from the meso-scale and cap tests and will likely consist of the FOS systems and PES. It is envisioned that active PES will be utilized as in the meso-scale test bed for detection of moisture gradients in biased locations and will be coordinated with the ERT sensors for detecting areas of moisture migration and cracking leading to preferential moisture paths. Passive PES will be used to detect cracking during the grout placement and active corrosion in the structural system (walls of the test tank will be used to simulate building construction above zero grade), and detect active cracking in the cap due to restrained shrinkage or corrosion. In the cap, PES will be deployed in a grid pattern, together with other appropriate sensor types.

For this test bed it is recommended that measurement frequency simulate as nearly as possible actual field conditions including the use of solar panels for energy and the use of wireless sensors wherever feasible. This will have implications for data acquisition rates and processing of the data to reduce the amount collected for interpretation.

5.2 SUBSURFACE MONITORING BELOW THE ISD STRUCTURE

Subsurface deployment of electrode strings in well holes will allow 3-D imaging of the resistivity in sand deposits below the -40 foot slab of 105-C. Fluid movement through the unsaturated sand deposits will change the resistivity of the sediments and can be mapped to monitor the potential release of fluid from the bottom of 105-C. Change in the resistivity of the sand deposits is possible from rain events if the ground around the 105-C building becomes saturated. The rain event is distinguished from the leaking events because it represents a transient event that dissipates and resistivity will return to pre-rain levels. A leaking event will be sustained by moisture seeping into the sediment, and the source can be triangulated inside 105-C.

In addition to the subsurface fluid monitoring using the ERT electrodes, selected fiber optic sensors from the meso-scale test bed are to be deployed to monitor key chemical compounds (ions and contaminants) in the fluids around the electrodes. This will provide complementary information on the source of the fluids, for example from a precipitation event or release from 105-C. The fiber optic-electrodes sensor package will serve as a long-term monitor to map out the history of the electrode degradation in the subsurface environment.

5.3 RESEARCH AND DEVELOPMENT FOR NEW SENSOR TECHNOLOGY

As discussed in Section 4.3, technologies to detect fluid concentrations and specific ions and leachates from the ISD structures do not currently exist. Promising research programs will be identified in FY11 and the research initiated in FY12 to allow two to three years of R&D prior to deployment of the sensor network in the full-scale test bed and in the 105-C structure. Various technologies to be explored include but are not limited to advanced fiber optic sensing and advanced piezoelectric sensors.

Although there is a wide variety of FOS for sensing different physical and chemical quantities, a multi-function, large scale fiber optic sensor network for simultaneously sensing multi-parameters does not exist. To date, sensing mechanisms (or transduction principles) of FOS have been well established [11, 39, 24, 37]. Although new sensing mechanisms are still being pursued, the driving force for future FOS development lies in *novel sensing platforms* and *enhanced performance*. The former means innovative sensing schemes, being technically and economically configurable with an existing sensor network and having a low manufacturing cost, while the latter means having desirable sensing qualities such as sensitivity and accuracy, with rapid response, and the ability to sense multiple parameters.

The research and development efforts for piezoelectric sensing should proceed along two fronts. The first and most important challenge for piezoelectric sensing is that the output from the sensors is in terms of waveforms that are not as immediately understood as other sensor outputs that are in terms of physical quantities such as strain or displacement. Therefore the primary emphasis of research approaches should be placed on data interpretation in both passive and active modes. Pattern recognition is promising for interpretation of piezoelectric data in passive mode [2] and algorithm development can be aided through the use of neural networks and similar approaches. The combination of active and passive sensing is promising where both approaches are feasible [35]. Model updating approaches hold promise for assessing the probability of detection and location of events and can aid in progressing from defect detection to structural health prognosis. The potential exists for not only detecting but also for 'mapping' areas of moisture between sensor arrays in active mode.

The second opportunity for research with piezoelectric sensing has to do with optimization and tailoring of the sensors themselves. COTS sensors have been developed for field use but have not necessarily been optimized to the materials expected to be encountered in the grout or concrete caps. This is particularly the case in active mode where high-amplitude pulsing of piezoelectric sensors will be advantageous to propagate the stress waves as far as possible in materials with high attenuation. For best results both the active and passive sensing elements should be optimized for the application envisioned.

Research achievements in these areas will be identified and evaluated based on whether the new technologies can be adapted and further developed for the ISD of 105-C facility. Research to design and develop these new sensors will require collaboration and technical exchange with university and industry research groups.

5.4 DEPLOYMENT OF STRUCTURAL SENSORS IN 105-C

Once data are evaluated from deployment of sensors in the meso-scale, model cap, and large-scale test bed, those sensors that exhibit the qualities that are required for long-term monitoring will be selected for installation. Deployment of structural sensors in the 105-C building and on the roof is envisioned to occur in FY14. These sensors will be preferentially placed in areas that are subjected to a high probability of cracking, corrosion or structural movement, such as construction joints and areas of known weakness. Structural sensors of interest include strain or displacement sensors, global positioning sensors, moisture sensors, rebar corrosion sensors and piezoelectric sensors. Infrared cameras to provide thermographic images of the open rooms and the presence of water in the building are also recommended for installation within the structure.

Lesson learned from networking within the large-scale test bed will be applied to deployment in the 105-C structure. Communication from the data loggers to the server and a user interface will be established during the short-term objectives. However the communication from sensors to loggers may need fine tuning, as the number of sensors placed and the distances between each sensor and loggers will be greater in the vast 105-C facility.

5.5 IMPROVING PERFORMANCE OF CONCRETE CAPS

Once improved concrete formulations are identified, recommendations will be made to the ACP engineering staff to use the superior formulations in the concrete caps in 105-C. Performance data from the laboratory tests and full-scale test bed will be the basis for the recommendation to change the present mixture to a high-performance concrete that provides increased durability and integrity.

The durability of reinforced concrete is typically controlled by the certainty of corrosion of the reinforcing steel. This has been recognized and there are currently several approaches taken to eliminate this failure mechanism:

- Casting of concrete monoliths containing no reinforcement (commonly referred to as plain concrete)
- Use of non-metallic fibers in place of structural reinforcement, such as nano, micro, or larger scale carbon or other fibers (application specific hybrid approaches can also be used).
- Substitution of steel reinforcement with materials that do not corrode in concrete. Commonly used non-metallic reinforcements are carbon fiber reinforced polymers (CFRP), glass fiber reinforced polymers, and aramid fiber reinforced polymers [1].
- Ductile concrete with a minimum tensile strain capacity of 2%, the ability to maintain tight crack widths below 50 micron, and with self-healing capability can be used to maintain water-tightness, and avoid steel corrosion [29, 30].

For the exterior cap (over the disassembly basin), the use of normal concrete or ductile concrete with CFRP reinforcing bars are potential solutions for long-term durability.

For the interior cap (over the reactor), impact resistance of the concrete material needs to be considered due to the potential for impact caused by falling debris associated with the expected degradation of the building structure above. For this application ductile concrete, with high damage tolerance under impact, and reinforced with CFRP, is a potential candidate. CFRP can be purchased either in the shape of rods that mimic typical steel reinforcement or in the form of grids. The use of grids has the advantage that the construction process is simplified due to handling and placing of the grid as opposed to individual reinforcing bars. The use of a concrete composite would ensure that the cap will maintain structural capacity and provide a barrier to water penetration for an extended period of time.

5.6 DEPLOYMENT OF PHYSICAL AND CHEMICAL SENSORS IN GROUT FILL AND CONCRETE CAPS

Deployment of physical and chemical sensors in below-grade rooms of 105-C and the concrete caps over the reactor and disassembly basin is expected to begin in FY14. Based on the findings from R&D efforts, the meso-scale and full-scale test beds, various sensors including moisture, resistivity, impedance, leakage, temperature, pressure, piezoelectric and chemical-specific sensors will be placed in biased locations, potentially as grid nets along the -40 foot level floor and as vertical strings between the -20 to -40 levels in the grout fill. Physical sensors will be placed in the concrete caps and will assess moisture, strain, temperature, crack growth/location, and rebar corrosion. Again, the sensor network communication is extremely important and determining wiring routes from sensors to the logger will not be trivial. Lessons learned from the test beds will aid in establishing the sensor network below grade.

This page intentionally left blank.

6.0 COST & SCHEDULE

The panel was tasked with determining the best path forward for remote monitoring of the 105-C structure and grout monolith, although the recommended approach and rough cost estimate is applicable complex-wide. Given the lengthy time requirements for preparing documents, operational logistics and expense of performing work on a DOE site, the consensus of the panel is that about $28M would be needed over a six-year period (FY11 through FY16) to select, design, test, and deploy sensors in a full-scale test bed, the high-performance concrete cap, the 105-C structure and in the subsurface below the 105-C building. Lowering this cost by eliminating the full-scale test bed is not a recommended option, as the panel concluded that most remote-monitoring data collected from the embedded sensors in the 105-C structure will be difficult to reduce and interpret, and are potentially meaningless, without first understanding the instrument performance and development of appropriate data interpretation algorithms under the ISD conditions simulated in the full-scale test bed.

Additionally, the panel concludes that available funding of $1.2M for FY11 would be best spent by organizing the sensor deployment team and collaborating on small projects that include a meso-scale test bed, testing of alternative cap concrete mixtures, and instrumentation of a reduced-scale concrete cap. These reduced-scale projects will build consensus among the team and address many potential issues on sensor types to deploy, wiring geometry for different systems, data recording, storage, transmission and sharing, data reduction/interpretation, and documentation requirements. The following sections summarize the rough cost estimate and schedule to implement the panel's recommendations.

6.1 FY11

Short-term objectives are based on a $1.2M funding scenario for FY11 (Figure 6.1) and are focused on data communication and collaboration between SRNL, ACP, and non-SRS PIs, off-site construction of a meso-scale test bed and reduced-scale cap to install and embed sensors in grout and concrete, and evaluation of high-performance concrete formulations for caps to be placed over the reactor and disassembly basin. The cost and schedule reflect the scope discussed in Section 4.0.

	FY11 $K		Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Communication and Documents	400											
Meso-Scale Test Bed	500											
Lab Test of Cap Concretes & Cap Model	300											

Figure 6.1 Rough estimate of cost and schedule for initiating work with a sensor deployment team.

6.2 FY12 THROUGH FY16

Long-term objectives are based on total funding of approximately $27M over five consecutive years (Figure 6.2). The summary below reflects the scope discussed in Section 5.0.

FY12 work focuses on data communication and collaboration between SRNL, ACP and non-SRS PIs, production of work and design documents, initial construction of a full-scale test bed in a portion of the empty water basin near 105-C, installation of the first wells for a subsurface electrical resistivity system, and identification of two to three viable research programs that can develop the next generation of physical and chemical sensors.

In FY13, work will continue on the full-scale test bed with the addition of instruments and grout and the placement of an instrumented high-performance concrete cap (or caps) above the test bed, assessment of instrument performance, expansion of the subsurface resistivity network, initiation of research programs to develop new sensors, integration of sensor deployment plans with the ACP planning process for 105-C, completion of work plans for structural sensors in 105-C, deployment of the first structural sensors in above-grade areas of 105-C, and initial recommendations to ACP on alternative high-performance concrete caps, including instrumentation.

FY14 will continue with work on assessing instrument performance from the full-scale test bed and the high-performance concrete cap(s), assessment of the subsurface resistivity network, assessment of the FY13 research efforts and expectations for research goals in FY14, integration of work with the ACP planning process, completion of work plans for physical and chemical sensors in below-grade areas of 105-C, deployment of the first sensors in below-grade areas of 105-C, and final recommendations to ACP on construction of high-performance concrete caps.

In FY15, efforts will focus on deployment of sensors in above and below-grade areas of 105-C, assessment of instrument performance from the full-scale test bed and high-performance concrete cap, assessment of the performance of the subsurface resistivity network, assessment of the FY14 research efforts and expectations for recommendations and deployment of new sensors in the full-scale test bed in FY16.

FY16 will begin with final deployment of sensors in the above-grade and below-grade areas of 105-C, testing of the systems prior to grouting, deployment of new sensors in the full-scale test bed (new sensors can be added to the test bed at any time) or 105- C, assessment of instrument performance from the full-scale test bed and high-performance concrete cap, assessment of the performance of the subsurface resistivity network, and the final expansion of the subsurface resistivity network.

	FY12 $K	FY13 $K	FY14 $K	FY15 $K	FY16 $K
Communication and Documents	1700	1300	700	800	650
Design, Construct and Operate Full-Scale Test Bed	2000	2000	500	500	500
Subsurface Resistivity System	1000	1000	500	500	1000
R&D Program for New Sensors	500	1500	1500	500	0
Deploy Structural Sensors in Caps and Above Grade	0	500	1000	1000	500
Deploy Physical & Chemical Sensors Below Grade	0	0	2000	1500	500
Cap Recommendations to ACP Engineering	200	500	500	0	0

Figure 6.2 Rough cost estimate and schedule to deploy remote-monitoring systems in a full-scale test bed, 105-C, and the subsurface sediments below 105-C.

7.0 REFERENCES

1. ACI 440.1R. 2006. "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars". Reported by ACI Committee 440, American Concrete Institute, Farmington Hills, MI. www.concrete.org.

2. Anastassopoulos, AA, Kouroussis, DA, Nikolaidis, VN, Proust, A, Dutton, AG, Blanch, MJ, et al. (2002), "Structural integrity evaluation of wind turbine blades using pattern recognition analysis on acoustic emission data", Proc. *25th European Conference on Acoustic Emission Testing (EWGAE 2002), Prague, Czech Republic, 11-13 Sep.*

3. ASTM C1202. "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration". ASTM International. West Conshohocken, PA. www.concrete.org.

4. ASTM C1581/C1581M. "Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage". ASTM International. West Conshohocken, PA. www.concrete.org.

5. ASTM D2434. "Standard Test Method for Permeability of Granular Soils (Constant Head)". ASTM International. West Conshohocken, PA. www.concrete.org.

6. Baldwin C, Poloso T, Chen P, Niemczuk J, Kiddy J and Ealy C. , 2001, "Structural monitoring of composite marine piles using fiber optic sensors", *Proceedings of SPIE: Smart Structures and Materials and Nondestructive Evaluation for Health Monitoring and Diagnostics*, vol. 4330. p. 487–97.

7. Bobbitt, John, Nicholas Vrettos, and Matthew Howard. 2010. *R & P Reactor Building In-Situ Decommissioning Visualization*. SRNL-STI-2010-00361.

8. Carey, S., 2008, Long-Term Assessment of P-105 Structure for in situ D&D Alternatives, Calculation T-CLC-P-00004, Savannah River Nuclear Solutions, Aiken, SC.

9. Galati, N., A. Nanni, G. Tumialan, and P. Ziehl. 2008. "In-Situ Evaluation of Two RC Slab Systems – Part I: Load Determination and Loading Procedure". *ASCE Journal of Performance of Constructed Facilities*, Volume 22, No. 4, pp. 207-216.

10. Golaski, L., P. Gebski, and K. Ono. 2002. "Diagnostics of Reinforced Concrete Bridges by Acoustic Emission". *Journal of Acoustic Emission,* Vol. 20, pp. 83-98.

11. Grattan, K. T. V., and T. Sun. 2000. "Fiber Optic Sensor Technology: An Overview", *Sens. Actuators A: Physical*, *A82*, 40-61.

12. Grimson, J., Commander, B., and Ziehl, P.. 2008. "Superload Evaluation of the Bonnet Carre' Spillway Bridge". *ASCE Journal of Performance of Constructed Facilities*, Volume 22, No. 4, pp. 253-263.

13. Gu H., Moslehy Y., Sanders D., Song G. and Mo Y.L., 2010, "Multi-functional Smart Aggregate-based Structural Health Monitoring of Circular Reinforced Concrete Columns subjected to Seismic Excitations", *Smart Materials and Structures,* 19(6), 065026(7pp).

14. Hearn, S., and C. Shield. 1997. "Acoustic Emission Monitoring As A Nondestructive Testing Technique In Reinforced Concrete". *ACI Materials Journal*, Vol. 94, No. 6, pp. 510-519.

15. Hou, T-C., and Lynch, J.P. (2009), "Electrical Impedance Tomographic Methods for Sensing Strain Fields and Crack Damage in Cementitious Structures," *Journal of Intelligent Material Systems and Structures*, Sage Publications, 20(11): 1363-1379.

16. Hubbell, J. M., and J.B. Sisson. 1998. Advanced tensiometer for shallow or deep soil water potential measurements. Soil Science. April. Vol. 163. No. 4. .271-277

17. Hubbell, J.M., 2009. Estimation of Temporal and Spatial Water Flux in a Deep Vadose Zone, Department of Geologic Science Dissertation, University of Idaho, INL/EXT-09-17340. p. 140.

18. LaBrecque D., Heath, G., Sharpe, R., and Versteeg, R., 2004, Autonomous monitoring of fluid movement using electrical resistivity tomography: Journal of Environmental and Engineering Geophysics, 9, 167-176.

19. LaBrecque, D., Sharpe, R., Wood, T., and Heath, G., 2004, Small-Scale electrical resistivity tomography of wet fractured rocks: Groundwater, 42, (1), 111-118.

20. Langton, Christine A.; M. G. Serrato, J. K. Blankenship, and W. B. Griffin. 2009. *Savannah River Site R-Reactor Disassembly Basin In-Situ Decommissioning – 1049*. SRNL-STI-2009-00807.

21. Lee, Patricia L; John B. Gladden, Timothy Jannik, Christine A. Langton, Michael G. Serrato, Chuck Urland, and Erick Reynolds. 2009. *Technology Requirements for In Situ Decommissioning Workshop Report*. SRNL-RP-2009-00269, Rev 0. Savannah River National Laboratory, Savannah River Site, Aiken, SC.

22. Liu, J.-G., Hattenberger and C.S., Borm, G., 2002, "Dynamic strain measurement with a fibre Bragg grating sensor system", *Measurement*, 32, 151–161.

23. Lu, Y. and Li, Z. 2008, "Cement-based piezoelectric sensor for acoustic emission detection in concrete structures", *Earth and Space Conference 2008: Proceedings of the 11th Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments*, v 323.

24. McDonagh, C.; C. S. Burke, and B. D. MacCraith. 2008. "Optical Chemical Sensors". *Chem. Rev.*, *108*, 400-22.

25. Moslehy_Y., Gu H., Belarbi A. , Mo Y. L. and Song G., 2010, "Smart aggregate-based damage detection of circular RC columns under cyclic combined load*ing*", *Smart Materials and Structures* , 19(6), 065021(12pp).

26. National Research Council of the National Academies. March 2009. *Advice on the Department of Energy's Cleanup Technology Roadmap: Gaps and Bridges*. National Academies Press. Washington, D.C. http://www.nap.edu/catalog/12603.html

27. Ohtsu, M. 1988. "Source Inversion Procedure for Acoustic Emission". *Progress in Acoustic Emission* 4 (1): 164–169.

28. Roctest http://roctest-group.com/

29. Sahmaran, M., and V. C. Li. 2007. "Transport Properties of Engineered Cementitious Composites under Chloride Exposure". *ACI Materials Journal*, Vol. 104, No. 6 Nov/Dec 2008, pp. 604-611.

30. Sahmaran, M.; V. C. Li, and C. Andrade. 2008. "Corrosion Resistance Performance of Steel-Reinforced Engineered Cementitious Composite Beams". *ACI Materials Journal*, Vol. 105, No. 3 May/June 2008, pp. 243-250.

31. Schechinger, B., and T. Vogel. 2007. "Acoustic Emission for Monitoring a Reinforced Concrete Beam Subject to Four-Point-Bending". *Construction and Building Materials* 21 (March): 483–490.

32. Song G., Gu H. and Mo Y. L. ,2008, "Smart aggregate: multi-functional sensors for concrete structures-a tutorial and review", *Smart Materials and Structures, 17, 033001*.

33. Song G., Gu H., Mo Y. L., Hsu T., and Dhonde H. , 2007, "Concrete structural health monitoring using embedded piezoceramic transducers", *Smart Materials and Structures,* 16, 959-968.

34. Tennyson RC, Mufti AA, Rizkalla S, Tadros G, Benmokrane B. , 2001, "Structural health monitoring of innovative bridges in Canada with fiber optic sensors", *Smart Materials and Structures*,10, 560-73.

35. Tsimogiannis, A., Gergali, B., and Anastassopoulos, A. (2000), "Acoustic emission/acousto-ultrasonic data fusion for damage evaluation of concrete", *Journal of Acoustic Emission*, 18:21-28.

36. U. S. Department of Energy (DOE). 2009. *DOE EM Strategy and Experience for In Situ Decommissioning*. Office of Environmental Management (EM), Office of Engineering and Technology (EM-20). Washington, DC.

37. Wang, C. 2009. "Fiber Loop Ringdown--A Time-Domain Sensing Technique For Multi-Function Fiber Optic Sensor Platforms: Current Status And Design Perspectives". *Sensors*, 9(10), 7595-7621.

38. Whelan MP. ; Albrecht D. and Capsoni A. 2002, “Remote structural monitoring of the cathedral of Como using an optical fiber Bragg sensor system”, *Proceedings of SPIE: Smart Structures and Materials and Nondestructive Evaluation for Health Monitoring and Diagnostics*, vol. 4694, 242–52.

39. Wolfbeis, O. S. 2008. “Fiber-Optic Chemical Sensors and Biosensors”. *Anal. Chem.*, *80*, 4269-83.

40. Xu, J. 2007. “Nondestructive Evaluation of Prestressed Concrete Structures by Means of Acoustic Emission Monitoring”. PhD Dissertation, Auburn, Alabama: Auburn University.

41. Yan S., Sun W., Song G., Gu H., Huo L-S, Liu B.and Zhang Y-G, 2009, “Health monitoring of reinforced concrete shear walls using smart aggregates”, *Smart Materials and Structures*, 18(4), 047001 (6pp).

42. Yoon, D.; J. Weiss, and S. Shah. 2000. “Assessing Damage in Corroded Reinforced Concrete Using Acoustic Emission”. *Journal of Engineering Mechanics* 126 (3): 273–283.

43. Yuyama, S.; A. Li, U. Ito, and M. Arazoe. 1999. “Quantitative Analysis of Fracture Process in RC Column by Moment Tensor Analysis of Acoustic Emission”. *Construction and Building Materials*, Vol. 13, p. 87-97.

44. Zhang M-H. , Li H. and Ou J-P, 2007, “PZT active health monitoring for fatigue accumulative damage of concrete beam containing nano-particles for pavement”, *Proceedings of the SPIE - The International Society for Optical Engineering*, 6595.

45. Zhao X.Y. and Li H.N., 2008, “Modal parameters identification of concrete structure based on built-in PZT sensors”, *Earth and Space Conference 2008: Proceedings of the 11th Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments*, v 323.